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CONSTRUCTION METHODS IN REDUCING RADON RISK IN NEW HOUSES

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ABSTRACT

Radon is a radioactive gas that can be detrimental to human beings if there is constant exposure to high levels of concentration. Most radon gas comes from the soil and enters houses through concrete floor slabs. The State of Florida has developed draft standards for the construction of radon-resistant houses to control and prevent radon entering houses. Supporting research has been conducted by the University of Florida (UF) and other agencies. Its main purpose is to evaluate the performance and effectiveness of particular features of the standards. Radon problems have been studied in the health sciences for years; however, the construction industry has not yet given them serious attention.

There are two main approaches in reducing radon concentration in houses. The passive approach uses construction techniques to reduce the rate of radon entry. These techniques include installing vapor barriers underneath the floor slab, properly sealing plumbing penetrations and slab cracks, and installing radon mitigation systems in the house. When the passive approach does not reduce indoor radon concentrations to an acceptable level, the active approach can be applied, in which fans are used to lower the air pressure below the slab. These two mitigation methods were applied by UF in fourteen new houses in 1992 and twelve in 1993.

This article presents radon test results, and estimates construction costs, materials requirements, and the time required to install the systems. The constructability of the two methods and their overall effectiveness are also discussed.

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INTRODUCTION

Radon is a colorless, odorless, radioactive gas released during the natural decay of thorium and uranium, which are found in rocks and soil. Constant exposure to high concentration levels of radon could cause lung cancer. An average of 14,000 people per year are said to die in the United States because of radon gas [1]; see Figure 1. The Environmental Protection Agency (EPA) has set a critical value of 4 $pCiL^{-1}$ (148 Bqm^{-3}); concentrations above this level are held to be potentially harmful to people [1].

The state of Florida has developed a draft standard for the construction of radon resistant houses that was evaluated in research conducted by the University of Florida (UF), the Florida Solar Energy Center, and GEOMET Technologies, Inc. The UF research teams were drawn from the Departments of Civil Engineering, Nuclear Engineering and Science, and Environmental Engineering, and from the School of Building Construction. The integration of these research disciplines played a crucial role in resolving radon problems. The results of 1992 and 1993 trials of radon mitigation measures are given in this article.

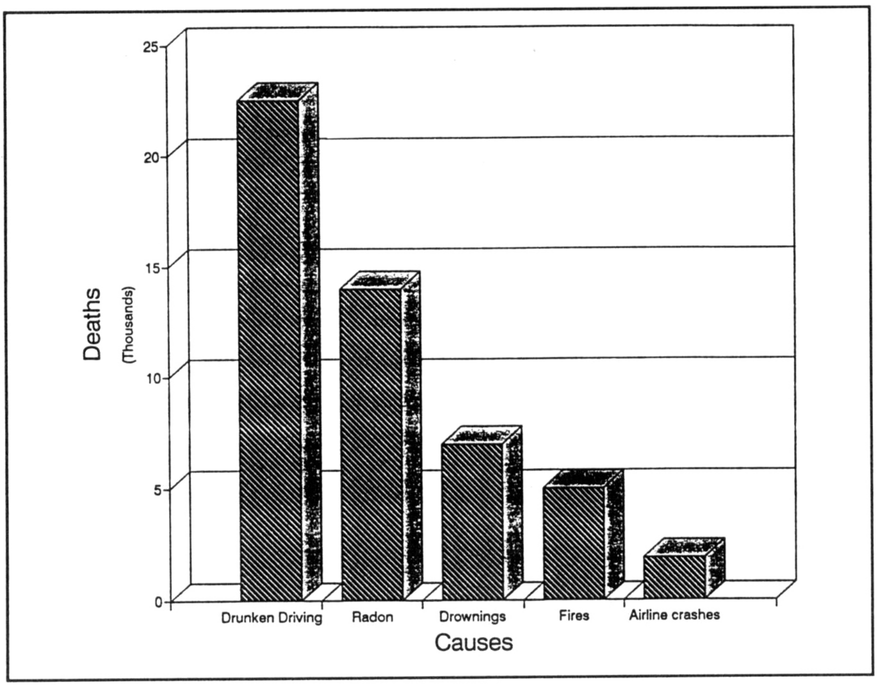


Figure 1. Causes of deaths [1].

OBJECTIVE OF THE RESEARCH

The purpose of the radon research was to evaluate the overall effectiveness of the draft Florida radon-resistant building standards. The standards are to be revised in light of the results. The effectiveness of three mitigation approaches were studied: 1) concrete floor slab, passive barrier systems; 2) slab-wall-foundation systems; and 3) HVAC (Heating, Ventilation, and Air Conditioning) systems. The Civil Engineering research team concentrated on construction processes and quality, crack formation, and proper installation of the mitigation systems.

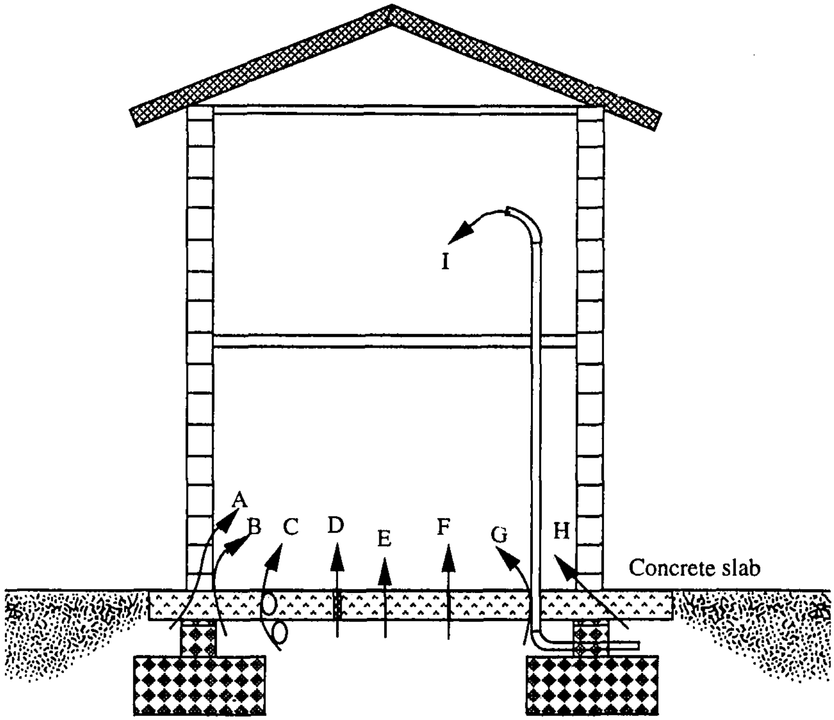
Radon gas can enter a house from underlying soil through cracks in concrete floors, plumbing penetrations, wall-floor connections, construction joints, and floor drains. The paths of radon entry are illustrated in Figure 2. The highest radon levels are found in basements and slab-on-grade houses. Diffusion and convection flow are the major mechanisms for radon entry. Pressure-driven flow is the major factor in radon elevation and which is affected by temperature, windspeed, type of HVAC systems, and other factors.

PRE-CONSTRUCTION PHASE: SELECTION OF THE HOUSE SITES

Site selection was the first step of the project. With the aid of geological and radon-concentration maps, potential sites were identified from recently granted building permits and from contacts with local builders. The primary criterion for site selection was a soil radon level greater than 1000 $pCiL^{-1}$ (37 $kBqm^{-3}$). Permission from the builders for prior-testing of the sites was also necessary. If the soil radon level was greater than 1000 $pCiL^{-1}$ (37 $kBqm^{-3}$), the house conformed to other research requirements (one story, one HVAC unit, etc.), and the homeowner agreed to participate, a contract was made to conduct the radon research project.

MONITORING AND INSTALLATION IN CONSTRUCTION PHASE

In the construction phase, the pouring of the floor slab, curing, interior construction, and house shell construction were monitored. Radon mitigation systems were installed simultaneously. This involved the following elements of the radon mitigation systems: 1) pressure field extension tube installation, 2) subslab depressurization: Enkavent mat or suction pit method, 3) vapor barrier placement, and 4) HVAC installation. Vapor barriers were extended over the edge of the slab, as illustrated in Figures 3 and 4 (modified from [2]).



A: Spaces behind brick veneer walls that rest on uncapped hollow-block foundation
B: Wall-floor joint
C: Heating duct registers or subslab cold-air return pipes
D: Control joints or saw cuts
E: Cracks in concrete slab
F: Cold joints between two concrete pours
G: Plumbing penetrations
H: Open tops of block walls
I: Water (Bathroom, kitchen)

Figure 2. Radon gas entry paths.

Construction Phase and Crack Tests

The two major tests in the construction phase were crack tests and pressure field extension measurements. Cracks were classified as hairline, fine, medium, or wide, depending on their widths. Each crack was tested for radon coming through the crack and pressure differentials. The pressure differentials determined the total equivalent crack area.

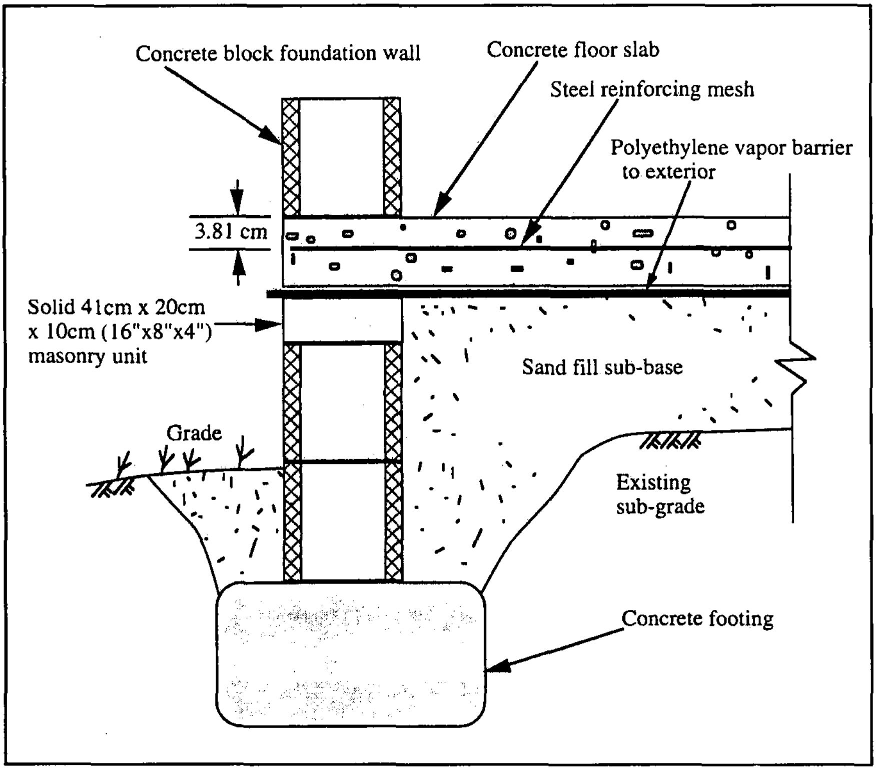


Figure 3. Vapor barrier placement: elevated slab.

Floor slab cracks were assumed to be one of the major radon entry routes that could elevate indoor radon levels significantly. To reduce crack development, superplasticizers were added before pouring, to increase workability of the concrete, and to minimize water use. The placement of corner rebars and the use of control joints also was found to be successful in reducing cracking.

In the 1993 installations, it was found that construction joints stopped crack extension effectively (see Figure 5 [3]). In most of the houses, cracks were prevented from developing owing to the proper design and placement of construction joints, proper curing methods, and enough curing time.

Cracks and construction joints were sealed with elastomeric sealants. The builders used the "saw cut" method for constructing construction joints, but declined to use the "T-split waterstop" because of increased construction costs. Available crack and joint sealants are listed in Tables 1 and 2 [2]. Crack repair methods and control joint installation are illustrated in Figures 6 and 7 (modified from [2]).

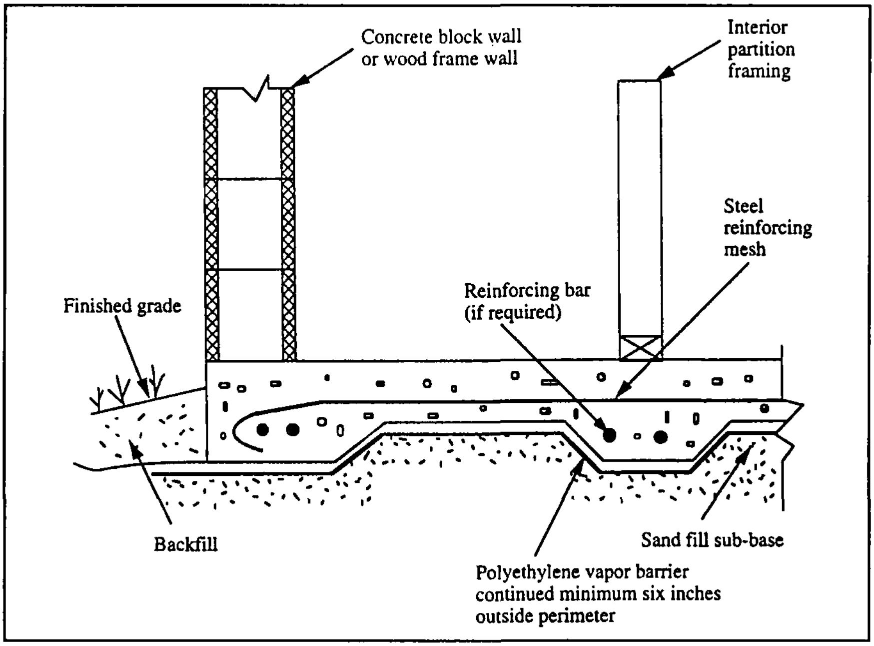


Figure 4. Vapor barrier placement: slab-on-grade.

In selecting sealants, it is essential to consider the ability of the sealant to deal with the movement of the joint or crack, or temperature changes. The ability of a sealant is qualified by its allowable extension and compression, elongation of rupture, hardness and recovery from compression.

RADON MITIGATION SYSTEMS

Enkavent Mat Method

Enkavent mat is about 18 inches wide and comes in 100-foot long rolls. A 2-inch vent pipe was placed on the Enkavent mat and extended through the roof. To prevent rain and pollutants from entering the vent pipe, a cap was installed at the end. The vent pipe carried subslab radon to the roof and ventilated it. The mat strips were oriented along the central axis of the longest dimension of the slab or diagonally across the slab. It is necessary to provide one mat strip for every 50 feet of slab width. Mat placement should start at a distance of 6 feet or more from the slab edge. The pipe should be centrally located along the length of each mat strip. One pipe should be provided for every 100 feet of mat length [4]. A typical layout is shown in Figure 8.

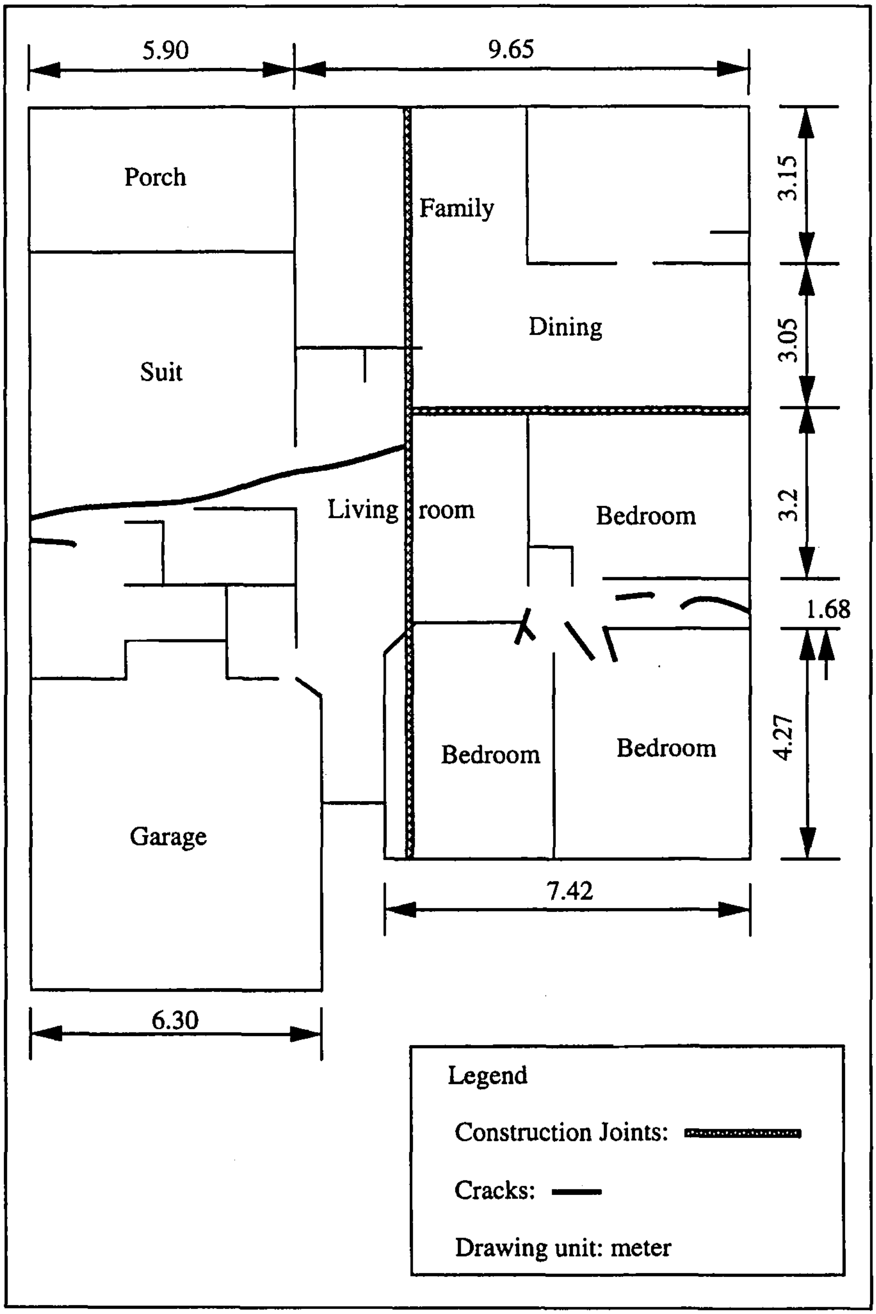


Figure 5. Crack map of house A11.

Table 1. Crack Sealants

Product Name or Number	Characteristics	Elongation (ASTM:D412)	Allowable Extension/ Compression (%)
Tremproof 60	One part, Bitumen Modified–Moisture curing polyurethane	950%	
Rely-on	Based roofing cement	N/A	
PR-318	One-part polyurethane coating	250%	
VIP #5100 Series	Buttering Grade Ter-polymer Acrylic	525%	+/– 25%
Vulkem 101 Grade L	One-Part Polyurethane	N/A	
Duramem H-500	Elastomeric Liquid Membrane	950%	
Dow Corning 795	Silicone	N/A	+/– 50%

Note: N/A = not available.

Suction Pit Method

The suction pit method is similar to the Enkavent mat method. Open or gravel pits are used in construction. The open pit is a semi-spherical hole 32 inches in diameter and 16 inches deep, with a vent pipe connecting the pit to the roof. Usually the vent pipe is placed vertically in an interior wall or a closet. A steel plate covers the top of the pit. A 2-inch collecting pipe in the pit rises 1/4 inch per horizontal foot. It is necessary to provide one 2-inch vent pipe for each pit.

The gravel pit is the same as the open pit, except the pit is filled with gravel and does not have a steel cover. The gravel pit has the advantage of being less hospitable to insects, and the disadvantage of greater susceptibility to obstruction of the vent pipe following earth movement or rain. A gravel pit is illustrated in Figure 9.

Table 2. Joint Sealants

Product Name or Number	Characteristics	Elongation ASTM (D412)	Joint Movement
Silkaflec 1a	One Component Polyurethane	700%	+/– 25%
Semistone	Two and Three part Epoxy polymer coating	100%	
NR-201	One-part polyurethane	N/A	
Permapol RC-25L	Multi-component polyurethane	600%	+/– 25%
Eucolasstic	Two-part Urethane	450%	
Vulkem 45	One-part Polyurethane		
Phenoseal	Acrylic	N/A	
Gesil N	One-part Silicone	N/A	+/– 50%

Note: N/A = not available.

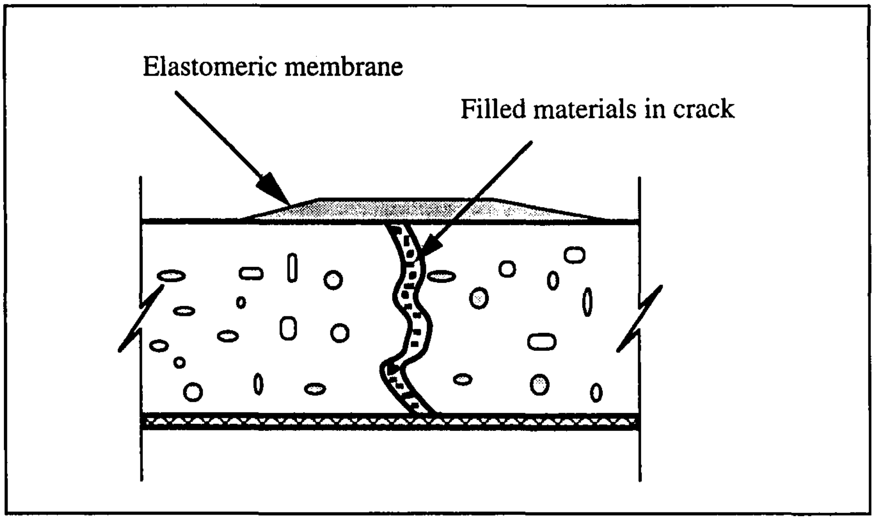


Figure 6. Crack repair.

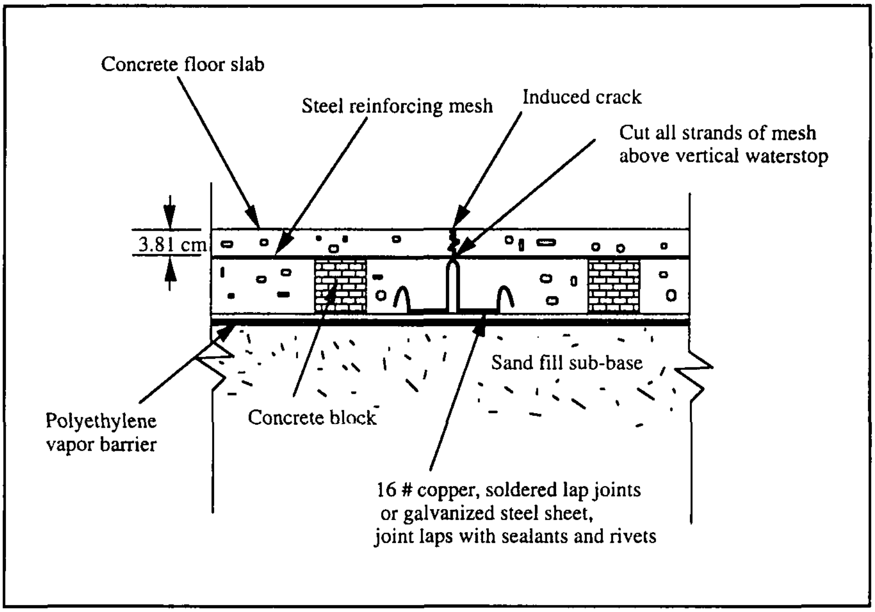


Figure 7. Control joint installation and sealants placement: waterstops, T shape.

PIPE CONSTRUCTION PHASE: INFILTRATION AND INDOOR RADON TESTS

In the post-construction phase, infiltration tests and indoor radon tests were conducted. Pressure differentials between indoor and subslab areas are the major forces driving radon infiltration. The pressure differentials are related to the ventilation rate (infiltration) of the house. Ventilation was measured under four conditions: 1) natural ventilation, all mechanical systems off, doors open; 2) air handler on, doors open; 3) air handler on, doors closed; 4) exhaust fan on, doors closed. The first three conditions were referred to as passive ventilation, the last as active ventilation. The test data of the 1992 project are shown in Table 3.

Mean values of air change per hour (ACH) were computed from test measurements using the SAS statistical package [5]. The hypothesis of the test statistics is:

Ho: $\mu_1 = \mu_2 = \mu_3 = \mu_4$; Ha: one of them not equal, where
μ_i = infiltration rate (air change per hour) of test i.

According to the program output, the F value is 35.07 and p-value is 0.0001. Therefore, Ho is rejected; i.e., the means are not all equal. In addition, from the Tukey's analysis [6], the output can be interpreted as $\mu_3 > \mu_2 > \mu_1 = \mu_4$ (refer to

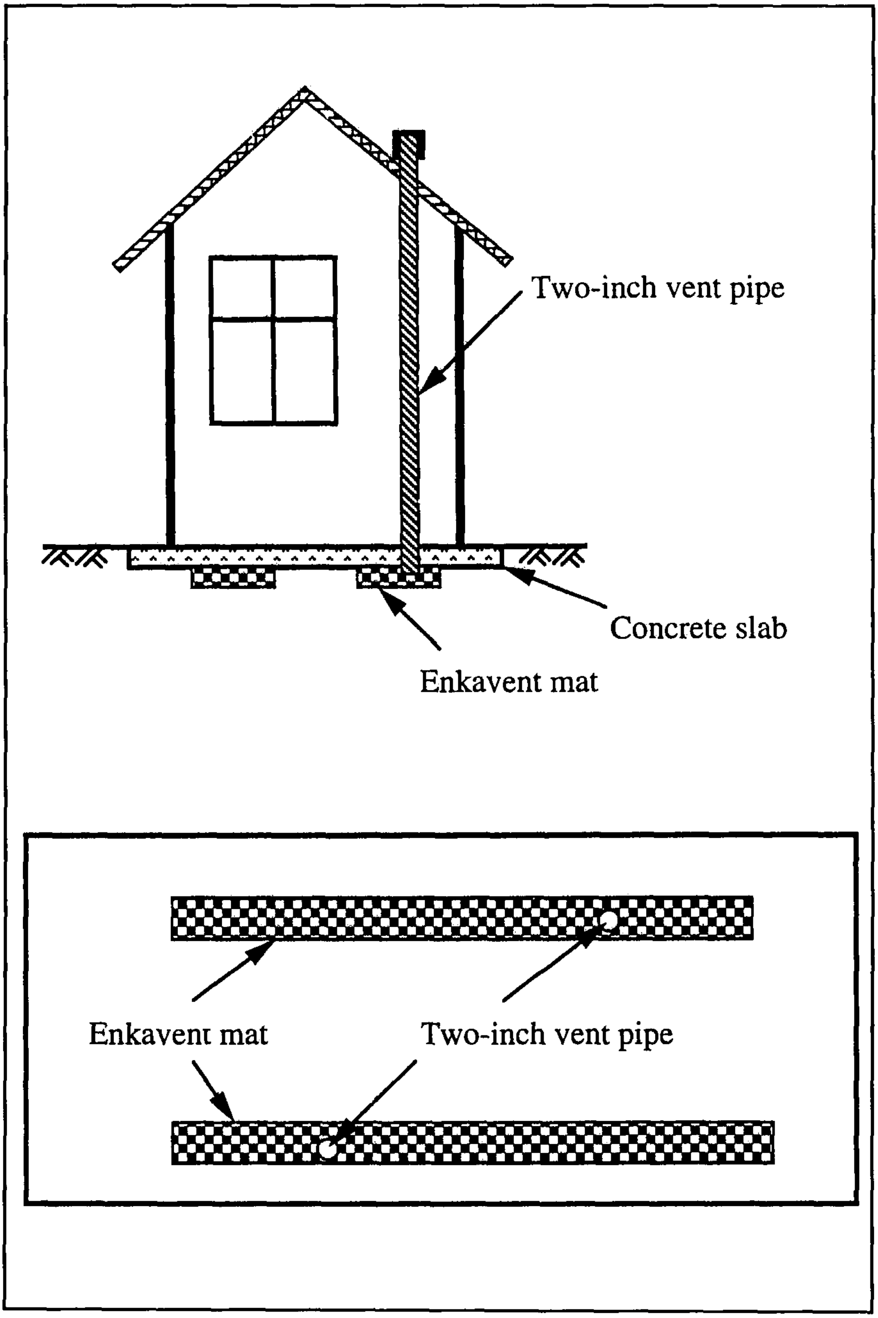


Figure 8. Enkavent mat layout.

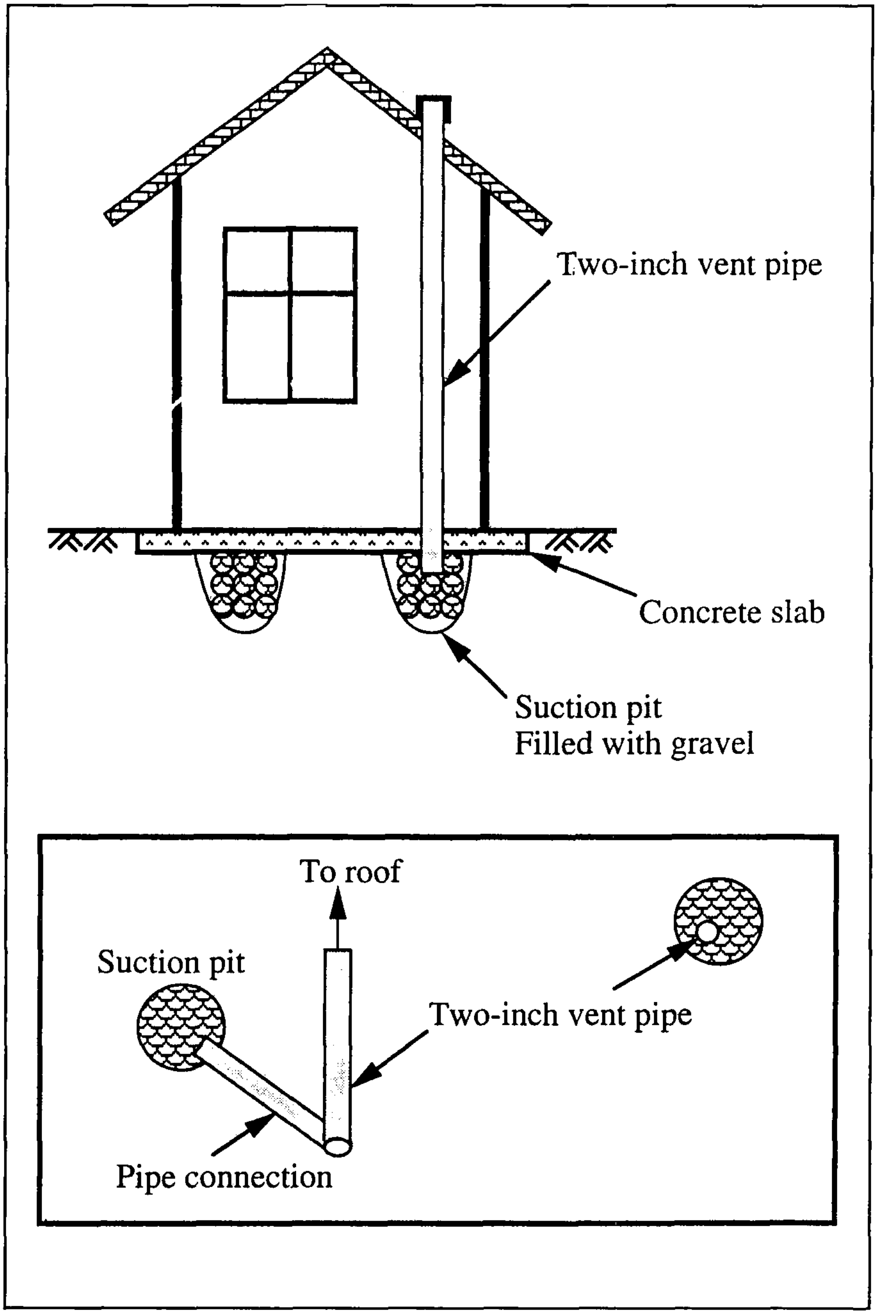


Figure 9. Gravel pit layout.

Table 3. Infiltration Rate (ACH) and Indoor Radon ($pCiL^{-1}$) Data.

	Test 1		Test 2		Test 3		Test 4	
House ID	ACH	Indoor Radon	ACH	Indoor Radon	ACH	Indoor Radon	ACH	Indoor Radon
ASGR1	0.144	2.3	0.327	1.2	0.626	1.6	0.169	0.8
HPBL1	0.495	5.3	0.424	6.8	0.557	5.4	0.159	N/A
RDTS1	0.215	1.5	0.317	1.2	0.631	1.0	0.188	N/A
OMMJ1	0.278	1.0	0.352	0.6	0.743	0.7	0.111	0.6
SOGR1	0.190	1.7	0.419	1.4	0.687	1.0	0.372	1.5
ASEM1	0.203	0.9	0.412	0.6	0.437	0.5	0.174	0.7
ASEM2	0.121	1.2	0.518	0.9	0.786	0.5	0.247	0.4
CFSH1	0.331	1.0	0.553	0.8	0.735	0.6	0.223	1.0
CHSH2	0.208	0.7	0.300	0.8	0.764	0.7	0.145	1.0
CFSH3	0.316	0.7	0.928	0.6	0.916	0.1	0.294	0.6
ASGR2	0.179	0.6	0.407	1.0	0.763	0.8	0.141	0.6
RDTS2	0.545	0.9	0.553	1.2	N/A	N/A	0.465	1.0
RBPE1	0.200	0.6	0.404	0.7	0.811	0.3	0.213	0.3
SOGR2	0.192	0.5	0.335	1.0	0.493	0.7	0.23	0.5
Average	0.258	1.35	0.446	1.342	0.688	1.069	0.223	0.75

Note: N/A = not available.

Tables 4 and 5). This result is as expected: the ACH is largest when the air handler is on with all doors closed, and the ACH is smallest when all mechanical systems are off with doors open. As shown in Figure 10, higher infiltration rates are associated with lower levels of indoor radon.

Radon Testing Data in Soil, Subslab, and Indoors

Radon concentrations for the two methods are shown in Tables 6 and 7. These data are below the 4 $pCiL^{-1}$ EPA standard except in two houses (HBPL1 and A11). Therefore, the two systems seem to reduce indoor radon levels quite effectively. For house HBPL1, the passive mitigation system failed to bring indoor radon levels to less than 4 $pCiL^{-1}$; the active approach was then applied. This reduced indoor radon concentrations to less than 1 $pCiL^{-1}$.

Table 4. Multiple Comparison of Means

General Linear Models Procedure
Dependent Variable: ACH

Source	*DF*	Sum of Squares	Mean Square	*F* Value	Pr > *F*
Model	3	1.8274903	0.6091634	35.07	0.0001
Error	51	0.8858327	0.0173696		
Corrected Total	54	2.7133230			

R-Square	C.V.	Root MSE	ACH Mean
0.673525	33.02920	0.1318	.3990182

Source	*DF*	Type I SS	Mean Square	*F* Value	Pr > *F*
TEST	3	1.8274903	0.6091634	35.07	0.0001

Source	*DF*	Type III SS	Mean Square	*F* Value	Pr > *F*
TEST	3	1.8274903	0.6091634	35.07	0.0001

CONSTRUCTION COST ESTIMATION

Materials and labor costs of the suction pit method are estimated in Table 8 [7]. The costs of the suction pit method are proportional to the floor area. However, if the floor area is divided into many sections, more pits may be needed. The cost is $517 for a typical three-bedroom house. This is a small fraction of the cost of the new house. As shown in Table 9, the Enkavent mat method is more expensive ($846), because the material costs of Enkavent mat is far costlier than gravel.

CONSTRUCTABILITY ANALYSIS

Several practical lessons emerged from the projects. The installation of mitigation systems should be allowed for in construction schedules; it was found that this can be done without disturbing the schedule for other construction activities, by fitting the installation of the mitigation systems into the "floats" among the other activities. The time required to install the system is about two to three days. The installation cost of a radon mitigation system, from $500 to $1000, is small enough to make them economically feasible. Builders' and homeowners' lack of

Table 5. Tukey's Comparison of Means

General Linear Models Procedure
Tukey's Studentized Range (HSD) Test for Variable: ACH
NOTE: This test controls the type I experimentwise error rate.
Alpha = 0.05 Confidence = 0.95 *df* = 51 MSE = 0.017369
Critical Value of Studentized Range = 3.756
Comparisons significant at the 0.05 level are indicated by ***.

TEST Comparison	Simultaneous Lower Confidence Limit	Difference Between Means	Simultaneous Upper Confidence Limit
3–2	0.1072	0.2420	0.3768***
3–1	0.2952	0.4300	0.5648***
3–4	0.3299	0.4647	0.5996***
2–3	0.3768	−0.2420	−0.1072***
2–1	0.0557	0.1880	0.3203***
2–4	0.0904	0.2227	0.3550***
1–3	−0.5648	−0.4300	−0.2952***
1–2	−0.3203	−0.1880	−0.0557***
1–4	−0.0976	0.0347	0.1670
4–3	−0.5996	−0.4647	−0.3299***
4–2	−0.3550	−0.2227	−0.0904***
4–1	−0.1670	−0.0347	0.0976

awareness of radon problems is an obstacle in having radon mitigation installed in houses. Governmental agencies should endeavor to educate people about the risks of radon. It is reasonable to expect that many homeowners would be willing to spend $1000 or less to have a safer living environment.

CONCLUSION

This article assess radon mitigation techniques for residential houses. Two systems, Enkavent mat and suction pit, worked well in reducing indoor radon concentrations. Techniques were developed to improve the performance of the mitigation systems.

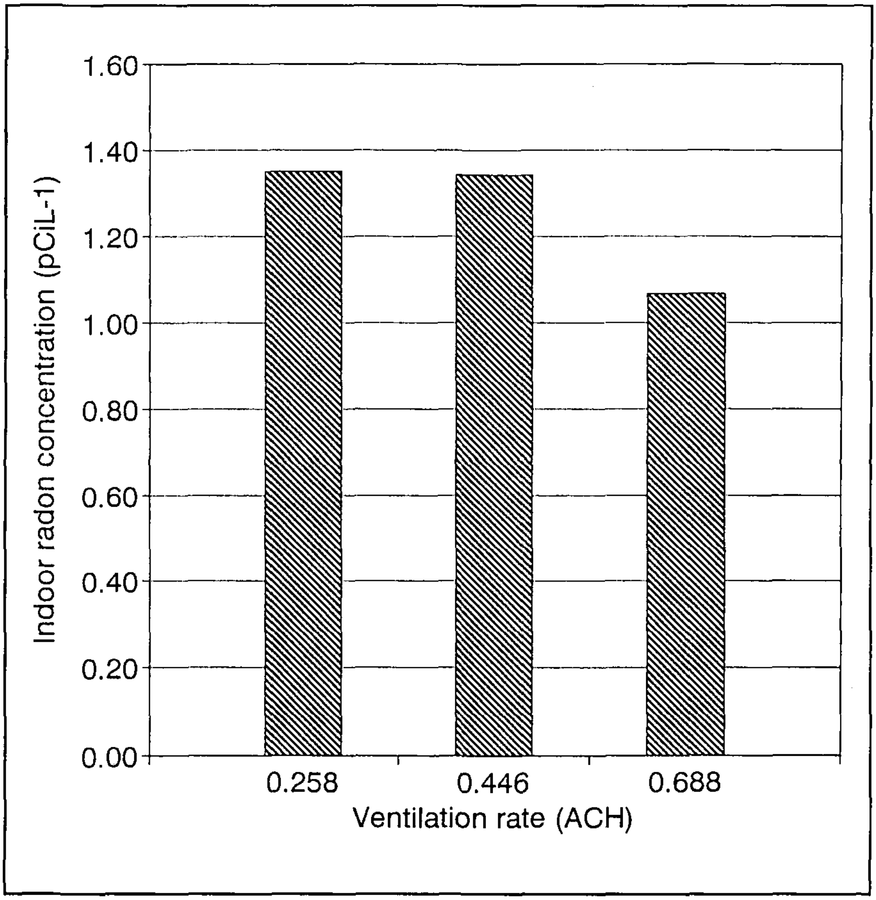


Figure 10. Infiltration rate vs. indoor radon concentration.

Table 6. Enkavent Mat Method (Project of 1992)

House ID	Soil Radon ($pCiL^{-1}$)	Subslab Radon ($pCiL^{-1}$)	Indoor Radon ($pCiL^{-1}$)
ASGR1	690	820	1.20
HPBL1	5300	7800	11.58
RDTS1	32000	1000	2.06
OMMJ1	2700	400	1.92
SOGR1	10000	3700	3.51
ASEM1	2100	860	0.56
ASEM2	11000	3700	0.97
CFSH1	2700	1600	1.71
CHSH2	1900	1900	2.13
CFSH3	5000	2200	2.52
ASGR2	1900	760	1.61
RDTS2	2800	2700	1.47
RBPE1	1400	510	0.93
SOGR2	2800	2100	2.66

Table 7. Suction Pit Method (Project of 1993)

House ID	Soil Radon ($pCiL^{-1}$)	Subslab Radon ($pCiL^{-1}$)	Indoor Radon ($pCiL^{-1}$)
A1	6982	N/A	N/A
A2	921	722	N/A
A3	10661	8482	2.60
A4	1055	3869	2.86
A5	1683	730	2.07
A6	2896	1223	2.52
A7	911	809	2.70
A8	1189	488	2.24
A9	2935	970	2.99
A10	6607	289	2.72
A11	1112	7484	4.16
A12	1289	1727	N/A

Note: N/A = not available.

Table 8. Cost of Gravel Pit Method

Average cost for gravel pits
House area = 3048 ft^2 (283 m^2)

Items	Material Costs ($)	Labor Costs ($)
Construction of pits	12	9
PVC supplies (pipe, flanges, bends, T's, Y's, etc.)	50.82	6
Tar (asphalt)	70	12
Curing Compound	47.15	3
Elastomeric sealants	49.7	12
Superplasticizer	245	0
Subtotal	474.67	42
Total	$517	

Table 9. Cost of Enkavent Mat Method

Average cost for Enkavent mat
House area = 3048 ft^2 (283 m^2)

Items	Material Costs ($)	Labor Costs ($)
Construction of mat	244	6
PVC supplies (pipe, flanges bends, T's, Y's, etc.)	50.82	6
Tar (asphalt)	70	12
Curing Compound	47.15	3
Elastomeric sealants	49.7	12
Superplasticizer	245	0
Subtotal	707	39
Total	$846	

The installation of the mitigation systems is easy, rapid, and economical. Builders can be trained in one- or two-day workshops. Radon mitigation systems are practical for the construction industry.

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